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**STRUCTURAL AND MANUFACTURING  
ANALYSIS OF A WING USING THE  
ADAPTIVE MODELING LANGUAGE**



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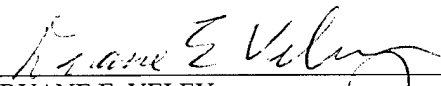
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# STRUCTURAL AND MANUFACTURING ANALYSIS OF A WING USING THE ADAPTIVE MODELING LANGUAGE

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## ABSTRACT

Computerized engineering architectures promise to significantly improve the process for designing complex systems. This paper investigates the application of the Adaptive Modeling Language® to the aircraft design process. Models were developed to perform a limited activity-based cost vs. structural performance trade study on a wing box. These disciplines were chosen because cost is becoming increasingly important in today's defense environment and it is not handled as systematically as the physics-based analyses by conventional aircraft design processes. Besides demonstrating the feasibility of combining diverse disciplines in a single engineering environment, this paper documents the time savings that can be realized by automating some repetitive design tasks.

## INTRODUCTION

The design of modern, cost-effective military aircraft requires the consideration of both cost and performance throughout the design process. This is relatively easy when considering an evolutionary design. When the engineer is familiar with the design space, experience is helpful in analyzing the necessary cost and performance trade-offs.

The design process is more complicated for a revolutionary design, either because of a new technology or a new configuration or both. The designer is, by definition, unfamiliar with the design space and consequently

will not be helped—and may even be led astray—by experience. Revolutionary designs require more physics-based and less historically based cost and performance analyses.

To perform these analyses rapidly, with a small team, and to insure that the necessary design data is available to both the cost and performance models, a modern computerized design framework is needed. This project is one of the many that will be needed to incorporate aerospace engineering disciplines in such a framework. The Air Force Research Laboratory is developing a number of modules that can be used for assessing the system level impacts of new technologies[1]. Industry is developing modules that can be used for the complete—design through manufacturing through support—development of a new aircraft.

For this project, TechnoSoft®, Inc.'s Adaptive Modeling Language (AML)[2] was used. AML was chosen because it is a mature, commercially available, architecture that already contained a number of objects that are needed for an aerospace design tool (e.g., geometric modeling, mesh generation, machining analysis, manufacturing process planning, etc.)

AML uses a unified part model paradigm. This paradigm allows all information about a part to be stored in a single hierarchical object model of the part. For instance, the part model of a wing can contain all the data needed for a panel method aerodynamic analysis, an equivalent plate structural analysis and a finite element analysis. Because some of the information is needed by all three analysis (i.e., span, chord lengths, sweep angles), using the part model concept simplifies the "bookkeeping" of the data and insures that all analyses are using the same values of the common information.

Along with the unified part model paradigm, AML's implementation of dependency tracking, demand-driven computation and an adaptive class structure were appealing. Dependency tracking allows the

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engineer to manage the feedforward and feedback of design information. The process of building an AML model requires the designer to connect various, closely related model components. AML automatically tracks these connections, resulting in a global model that may reveal distant interdependencies.

The demand-driven calculation feature allows complex models to be manipulated efficiently. For example, the wing span obviously affects both the aerodynamic and structural models of the wing. With demand-driven calculations, if the engineer is only working with the aerodynamic characteristics at a given time, AML does not update the structural model; thus saving calculation time.

The adaptive class structure allows the addition of new objects to a model that has already been instantiated. These new objects may also be connected to the existing model. This feature eliminates the need for a predefined "superclass". For example, a structural engineer can build a model of the wing for use with an equivalent plate analysis. If a second engineer has a model for performing a panel method aerodynamic analysis, these models can be combined without restarting or creating a new class consisting of both models—a superclass—and instantiating an object of that class.

For this project, the necessary AML models were constructed for combining two distinct types of analysis. An ASTROS[3] static aeroelastic finite element analysis was linked to an activity based cost model. This connection allowed cost and structural performance to be analyzed in the same engineering environment. The capability was exercised by performing a small (12 case) trade study.

## METHODOLOGY

### Surface Modeling of the Wing

The first step in this wing design process is to specify the outer moldline. This is accomplished by inputting the planform parameters and airfoil section(s). An AML model has been created that will generate the OML surface. A sample OML surface is shown in Figure 1. It should be noted here that the AML OML model is capable of generating a model from a planform with an arbitrary number of panels. Figure 1 shows a two panel lambda wing model.

Once the planform(s) has been modeled, a grid is generated on each planform panel. (Note: It is not necessary to calculate the OML surface for this step. It is only required that the planform parameters have been entered.) The grid will be used to associate the substructure (i.e., spars, ribs and stiffeners) with the planform. A sample grid and substructure layout are shown in Figure 2.

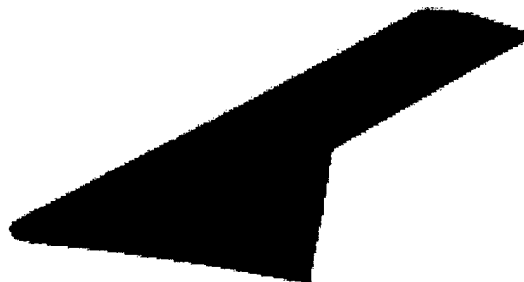


Figure 1: Wing Outer Moldline Surface

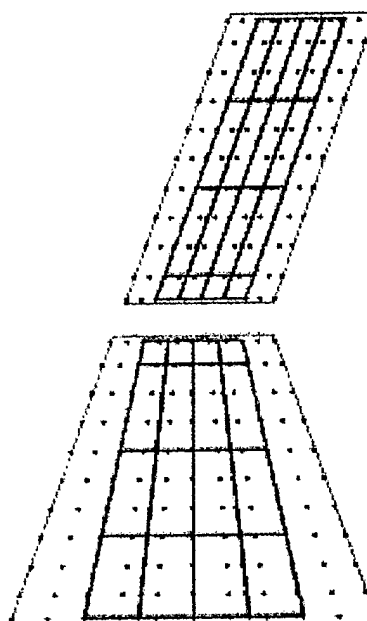


Figure 2: Substructural Layout Tool

The positions of grid vertices are determined relative to the planform. Grid lines (not shown) are laid out on the planform in terms of their chordwise or spanwise locations. The intersections of these grid lines generate the vertices. If the planform parameters (e.g., chord lengths, span, sweep angle) are changed, the grid lines and associated grid points can be recomputed according to their spanwise and chordwise locations.

As the grid vertices move, they "remember" the substructure elements with which they are associated. The new locations of the substructure can then be calculated automatically.

A surface (3-D) model of the substructure, Figure 3, can be generated from the substructure line model, Figure 2, and the wing OML model, Figure 1. The substructure lines are projected to the surface. The projected stiffener lines are used directly to model the stiffeners. The projected spar and rib lines are then skinned to cre-

ate the rib and spar surfaces. The projected leading edge and trailing edge spar lines, as well as the root and tip rib lines, are used to trim the OML to create the upper and lower surface of the wingbox.

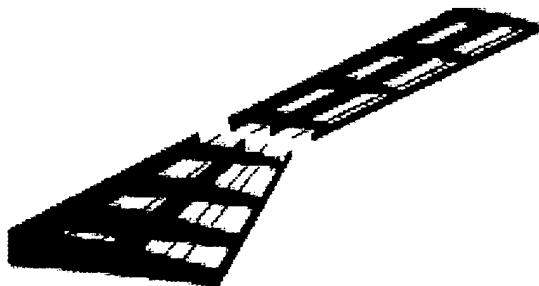


Figure 3: Substructure Surface Model - Lambda

#### Finite Element Modeling of the Wing

After the wingbox surfaces are created, AML's native mesh generation utilities are used to calculate the grid points and connectivities for a finite element model of the wingbox. A sample FEM mesh is shown in Figure 4. This mesh can be interrogated in a surface-by-surface (curve-by-curve, point-by-point) manner. In other words, all the node points or elements associated with a given surface can be determined.

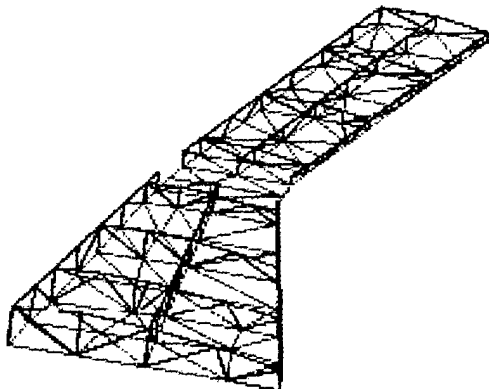


Figure 4: Finite Element Model Mesh

The reason for generating a FEM of the wingbox is to perform an ASTROS structural optimization to determine the thicknesses of the structural elements. The mesh is only a small part of an ASTROS model. The elements need to be associated with materials (specifically, with material properties), thicknesses—cross-sectional areas—and laminate properties (i.e., stacking sequence and fiber directions) for composite materials.

Additionally, for an optimization problem, the design variables, constraints and loading conditions

need to be specified. The default—minimum weight—objective function was used for this project.

The design variables were element thickness (layer thickness for composite elements) and the constraints were element (layer) stresses. The design variables were chosen on a structure-by-structure (e.g., spar-by-spar) basis. In other words, all the elements on a given spar are uniformly resized or they are not. The constraints were chosen on a material by material basis (i.e., all the elements modeled using a material were constrained or they were not).

A number of user interface screens were created for specifying these parameters. The model used for this project associated the materials, thicknesses, laminate properties and design variable information with each surface (curve). The material properties and constraint information were stored in a central material catalog, which was referenced by each surface.

Objects were also developed to store the information needed for specifying a static aeroelastic loading condition (i.e., the paneling for the USSAERO aerodynamic model; the spline connecting the aerodynamic and structural models; the flight condition, and the executive and solution control packets).

Once all the data was captured in the AML objects for a design problem, it was straightforward to create the complete ASTROS input deck by looping through the list of necessary objects.

#### Cost Modeling of the Wing

Once the optimally sized structure was determined for each configuration, it was desired to compare the manufacturing costs for each of the candidate designs. To accomplish this, an activity based cost model was developed in AML. The cost model is based on a preliminary level manufacturing analysis. It calculates both the one time and per piece costs for producing a wing with this manufacturing process.

Because a manufacturing analysis was used for the cost model, it must be tuned to a specific manufacturing plant. Parameters such as labor rates, skill factors for the workforce, raw material costs (normalized on a per quantity basis) and the time required for baseline tasks must be set for each manufacturing plant.

The one time costs are associated with fabricating the molds for laying up the composite skins and the fixtures for assembling the wing. This model assumed that the wing substructures were laid up in place, using the assembly fixtures as their molds.

The cost for the skin molds is estimated by calculating the surface area of the skin, multiplying that by a machining time per unit area and a cost per unit time for machining. This estimate should be more accurate than one based on the weight of the skin. Machining time—

and cost—for a mold does not depend on the weight of the part that will be made with the mold. The cost of the fixturing is estimated using a similar relationship. This cost is based on the length of the substructures.

The costs of laying up the spars, ribs and skins were also estimated using an activity based methodology. First, the number of layers in each component were calculated by dividing the part thickness by the material's ply thickness. The number of cuts and total length of the cuts were then estimated by using the part's surface area, the width of the raw material and a rule for the maximum length of any ply run. This rule is based on the maximum length that can be handled at the cutting or layup stations. The number of cuts and their total length are used to determine the time (and cost) for cutting and inspecting the build package for each component.

After analyzing the build package, the next step estimates the cost of assembling the part in the mold. This activity was modeled as three steps. First, the time to setup (i.e., clean and inspect) the molds was calculated. Next, the time to layup the plies in the mold was estimate. Finally, the cost of bagging and preparing the part for the autoclave was determined. The times for these operations were again estimated based on geometric characteristics (i.e., length, area and thickness) of the part.

The next step in this manufacturing process is to attach the stiffeners to the skins. (Note: the stiffener is treated as a raw material with a fixed cost per unit length.) This step is modeled in three tasks: setup, bonding and inspection. The time for each of these steps is calculated by multiplying a time per unit length of stiffener by the total length of all the stiffeners. The normalized times may be different for each of the tasks. Again, time and cost are assumed to be proportional.

The penultimate step in manufacturing this wing box is to assemble the spars and ribs and attach them to the lower surface. The cost model for this step is similar to the stiffener attachment cost model. The same three tasks were assumed for this step and the cost of each task was based on the length of the spars and ribs that are being attached to the lower skin.

The final step is to attach the upper skin to the wing box. Although it was not used for this project, the cost model for this step also includes the time for installing subsystems (e.g., wiring harnesses, fuel lines). Because this step consists of bonding the skin to the substructure, it is again based on the length of the spars and ribs. The only difference is the amount of time per unit length that a task is expected to consume.

## RESULTS

These design and engineering objects were evaluated by performing a trade study on a wing box. This study analyzed the trade-offs among the wing's structural layout, outer moldline and manufacturing cost. The AML models were used to generate 12 ASTROS finite element models, each with a different set of geometric parameters (i.e., airfoil section, planform and substructural layout). The values of the geometric parameters that were used for this study are given in Table 1. Figure 5 shows the surface model of the wing substructure for the conventional swept wing planform and the first substructural arrangement listed in Table 1. Figure 3 shows a similar model corresponding to the lambda wing planform.

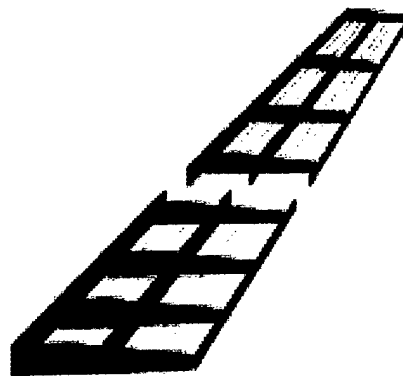


Figure 5: Substructure Surface Model - Conventional

In each of the ASTROS models, the upper and lower skins were modeled as a (0, 90, 45, -45) laminate of graphite-epoxy. The spars and ribs were modeled as "black aluminum" with averaged graphite-epoxy material properties. The stiffeners were modeled as rods with the same averaged "black aluminum" properties. Besides the geometric surfaces that can be seen in Figure 3, bar elements were added to connect the two substructural boxes. These elements were needed to represent the substructure that would be in the inter-panel region. To maintain the generality of the model, no attempt was made to model the geometry of the inter-panel region.

Each of the ASTROS models was sized to determine the minimum weight structure, of the given configuration, that will sustain a specified loading condition. The design variables were the thicknesses of: each spar; each rib; the 0° layer of the top skin; the 0° layer of the bottom skin; the 90° layer of the top skin; the 90° layer of the bottom skin; the 45° and -45° layers (together) of the top skin and the 45° and -45° layers (together) of the bottom skin. The spars and ribs were designed independently for each wing panel. In total,

Table 1: Trade Study Geometric Parameters

Airfoil Sections	4412
	4410
	3408
Planforms	<u>Conventional Swept Wing</u> Chord 1 = 47.864 Chord 2 = 31.83 Chord 3 = 15.795 Semispan 1 = 48 Semispan 2 = 48 Sweep 1/4 Chord = 28° Dihedral (both panels) = 5° Linear Twist, 5° tip up Wing Planform Area = 6111.2
	<u>Lambda Wing</u> Chord 1 = 58.04 Chord 2 = 23.1 Chord 3 = 23.1 Semispan 1 = 48 Semispan 2 = 48 Sweep Leading Edge = 20° Dihedral (both panels) = 5° Linear Twist, 5° tip up Wing Planform Area = 6112.4
Substructural Arrangements	Wing Box LE Spar @ 20% Wing Box TE Spar @ 80% One Spar @ 50% Two Stiffeners @ 35%, 65% Six Ribs = 15%, 20%, 45%, 55%, 70%, 85%
	Wing Box LE Spar @ 20% Wing Box TE Spar @ 80% Two Spars @ 37%, 63% One Stiffener @ 50% Four Ribs = 21%, 42%, 58%, 79%

there were 20 design variables for each case; three upper skin, three lower skin, six (or eight) spar and eight (or six) rib variables.

The constraints were the stresses in each of the elements. The constraint set included the stresses in the stiffeners and the interpanel bar elements, even though these elements were not used as design variables. The loading condition was 3g symmetric pull-up maneuver.

The weight of the rest of the airplane was modeled as a 4500 lbs. lumped mass.

The optimized skin and spar thicknesses are shown in Figure 6 through Figure 11. The thicknesses were normalized using the same factor for each design variable across all the graphs. That is, the same factor was used for the top skin 0° layer in all six graphs, but that factor is not necessarily the same one used to normalize the leading edge root spar thicknesses. The thicknesses of the rib elements showed very little variation among the cases so they were not graphed. This behavior was expected because, for this loading condition, the ribs were only used to maintain the outer moldline shape.

Figure 6: Conventional Wing - Three Spars

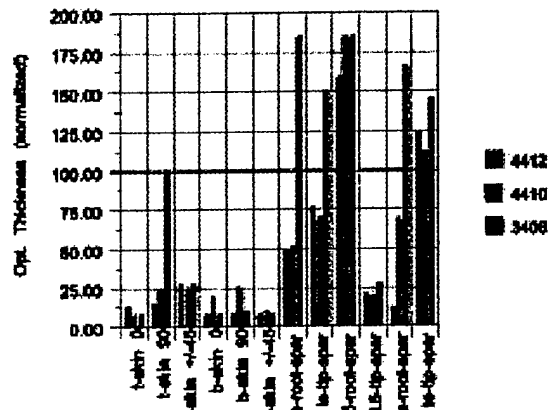
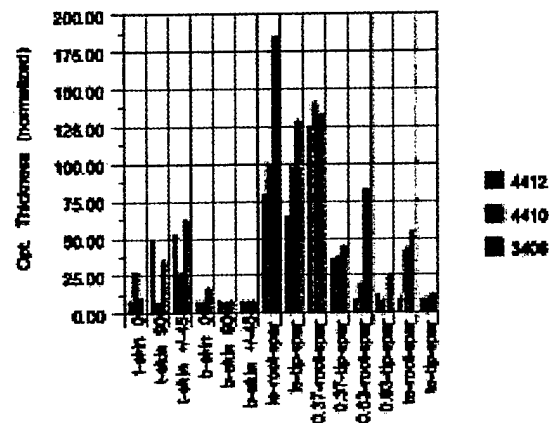


Figure 7: Conventional Wing - Four Spars



The conventional swept wing is more intuitive, so the discussion of results will start with that case. Looking at Figure 6 and Figure 7, it can be seen that, in general, the spars and skins are thicker for the thinner airfoil (NACA 3408). This result is consistent with an

A bar chart titled 'Opt Thickness (normalized)' on the y-axis, which ranges from 0.00 to 500.00 in increments of 50.00. The x-axis lists 14 conditions: Latin 0, Latin 50, Latin 100, Latin 150, Latin 200, Latin 250, Latin 300, Latin 350, Latin 400, Latin 450, Latin 500, Latin 550, Latin 600, and Latin 650. For each condition, there are three bars representing different values: 4412 (dark grey), 4410 (medium grey), and 3408 (light grey). The chart shows that for most conditions, the 'Opt Thickness' is relatively low (below 100). However, for 'Latin 100', the '4412' value is significantly higher, reaching approximately 480. For 'Latin 150', the '4412' value is around 320. For 'Latin 200', the '4412' value is around 240. For 'Latin 250', the '4412' value is around 200. For 'Latin 300', the '4412' value is around 180. For 'Latin 350', the '4412' value is around 160. For 'Latin 400', the '4412' value is around 140. For 'Latin 450', the '4412' value is around 120. For 'Latin 500', the '4412' value is around 100. For 'Latin 550', the '4412' value is around 80. For 'Latin 600', the '4412' value is around 60. For 'Latin 650', the '4412' value is around 40. The '4410' and '3408' values are generally lower than the '4412' values, with '4410' values ranging from approximately 100 to 200 and '3408' values ranging from approximately 20 to 100.

Condition	4412	4410	3408
Latin 0	20	20	20
Latin 50	20	20	20
Latin 100	480	240	20
Latin 150	320	20	20
Latin 200	240	20	20
Latin 250	200	20	20
Latin 300	180	20	20
Latin 350	160	20	20
Latin 400	140	20	20
Latin 450	120	20	20
Latin 500	100	140	100
Latin 550	80	140	100
Latin 600	60	180	100
Latin 650	40	180	100

[illegible]

Condition	Sweep	Laminar
1-0-0-0	0.00	0.00
1-0-0-0.5	100.00	230.00
1-0-0-1	100.00	230.00
1-0-0-1.5	100.00	230.00
1-0-0-2	100.00	230.00
1-0-0-2.5	100.00	230.00
1-0-0-3	100.00	230.00
1-0-0-3.5	100.00	230.00
1-0-0-4	100.00	230.00
1-0-0-4.5	100.00	230.00
1-0-0-5	100.00	230.00
1-0-0-5.5	100.00	230.00
1-0-0-6	100.00	230.00
1-0-0-6.5	100.00	230.00
1-0-0-7	100.00	230.00
1-0-0-7.5	100.00	230.00
1-0-0-8	100.00	230.00
1-0-0-8.5	100.00	230.00
1-0-0-9	100.00	230.00
1-0-0-9.5	100.00	230.00
1-0-0-10	100.00	230.00

[illegible]

The thickness trends are reinforced by analyzing the weight of the sized wing box in Figure 12. Ignoring for the moment the x-axis (cost), it can be seen that for the conventional swept wing (symbols z, &, %, #, x and >), the wing boxes with the 3408 airfoil section (symbols % and >) are the heaviest.

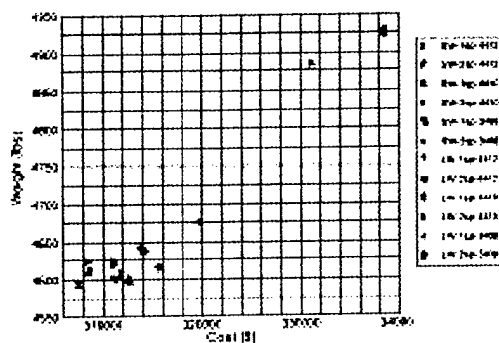
Figure 1 is a scatter plot showing the relationship between Weight (lbs) on the Y-axis and Cost (\$) on the X-axis. The Y-axis ranges from 450 to 478 in increments of 8. The X-axis ranges from 30,000 to 320,000 in increments of 10,000. There are 15 data points plotted. A legend on the right lists 15 different regression models, each with a corresponding symbol. The models include various combinations of polynomial degrees (1st, 2nd, 3rd, 4th, 5th, 6th, 7th) and step functions (1st, 2nd, 3rd, 4th, 5th, 6th, 7th).

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generally thicker. Additionally, it can be seen from Figure 12 that the 3408 cases (symbols < and g) are heavier than the 4412 cases (symbols ? and w).

The authors believe that the lambda wing cases with the NACA 4410 airfoil section have converged to a local minimum. Without performing a detailed analysis of the optimization history, this conclusion was made from an analysis of Figure 8, Figure 9 and Figure 13. Examining the thicknesses, the NACA 4410 cases resulted in much thicker upper skins and a few significantly thinner spars. The more compelling evidence is available in Figure 13. The other ten cases form a tight group; whereas the two lambda wing, NACA 4410 cases show significant differences both in cost and weight.

Figure 13: Weight vs. Cost - All Cases



After ensuring that the weight and stress design trends seem reasonable, the main focus of this trade study can be analyzed, cost vs. performance. It can be seen from Figure 12 that there is a clear winner in the cost vs. weight trade-off. The conventional swept wing with two intermediate spars and a NACA 4410 airfoil section is both the lightest weight and minimum cost design.

When the conventional preliminary design criterion of minimum weight is applied alone, this choice is not as obvious. Figure 12 shows that both of the conventional swept wings with 4410 airfoils (symbols x and &) are the least weight designs. This is consistent with reference [6], where it was shown that the minimum weight design is generally insensitive to the number of spars or ribs.

Along with enabling the cost vs. weight trade study in one environment, the program developed for this paper significantly reduced the time needed to generate the ASTROS models. Conventionally, the generation of the FEM model is a time consuming process and it must be redone for each change in the substructural arrangement or outer moldline of the wing. The process developed for this project took about 2.5 minutes of wall

clock time on an SGI R10000 processor to generate a complete ASTROS input deck. This time is just the computing time used after the parameters have been entered.

However, the raw computing time is not a complete measure of the time needed for a designer to use this system. A user familiar with the system was able to generate an ASTROS input deck from a cold start in about 20 minutes. This process included: inputting the parameters for the wing OML; laying out the substructure; generating the FEM mesh; assigning design variable values, materials and constraints; and specifying the aeroelastic loading condition. Including the approximately 5 minutes of wall clock time to run the ASTROS optimization on an SGI R10000, an experienced user could generate and run all twelve cases for this sample design study in less than a day.

## CONCLUSIONS

This project successfully demonstrated the use of a static aeroelastic finite element model and an activity based cost model in the same engineering framework. The goals of this project were to show that such a connection was feasible, to examine the potential labor savings of using an engineering architecture and to explore the design process that could be built using advanced engineering tools.

The purpose of this project was not to design a wing box; it was to explore the design process. Although the trade study conducted here was simplified from ones needed to design a production wing, the authors believe that all the disciplines necessary to design an aircraft can be integrated in the AML environment. Further, they believe that similar decreases in design time can be realized for other disciplines by modeling the design process in AML.

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